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Terahertz emission of SiGe/Si quantum wells doped with shallow acceptors

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Abstract. THz emission of stimulated character is observed in Si/SiGe/Si quantum well (QW) structures doped with boron. The resonance cavity formed by well parallel QW structure planes owing total internal reflection is necessary for the emission. The model of possible population inversion of strain-split acceptor levels is proposed.

Introduction

The stimulated terahertz emission of uniaxially stressed p-Ge [1] has been shown to be due to a population inversion of strain-split acceptor levels, one of them being in the continuum creating a so-called resonant state. The inversion mechanism consist in depopulation of the ground state of an acceptor (being in the gap) by strong electric field while the resonant state (being in the continuum) is filled to some degree because of exchanging carriers with valence band states. The intra-center population inversion seems to be rather general since the resonant states can arise by quite different reasons. In particular, they should exist in strained QWs where acceptor states are split with no external stress due to internal strain and/or size quantization. In this report we present the data of intense terahertz emission of boron doped $Si/Ge_xSi_{1-x}/Si$ QWs and propose an inversion mechanism similar to that in bulk p-Ge.

1. Experimental

The p-type $Si/Ge_xSi_{1-x}/Si$ QW structures MBE-grown pseudomorphically on the n-type Si substrate and selectively doped with boron were studied at the temperatures of 4 to 100 K. The Ge content x in SiGe alloy was 0.15. The SiGe layer of 20 nm thickness was δ-doped with boron in the QW middle with the concentration of 6×10^{11} cm^{-2}. It was sandwiched between undoped Si buffer (130 nm wide) and cap (60 nm) layers. Two boron δ-layers with B concentration of 4×10^{11} to 10^{12} cm^{-2} positioned within the buffer and cap layers on the distance of 30 nm from each QW interface were aimed to supply holes into the QW. The buffer δ-layer should also supply holes to form a p–n junction between the p-layers and the n-substrate. High voltage pulses of 0.3 μs duration (at luminescence measurements) or small dc voltage (at transport measurements) were applied along the QW to the ohmic contacts. The contacts were deposited on the p-side of the structure so that the p–n junctions prevented from a current by-pass through the substrate. Terahertz luminescence was registered by a cooled gallium-doped Ge photodetector sensitive above 10 meV. We studied terahertz emission of the structures arisen at high electric fields applied.

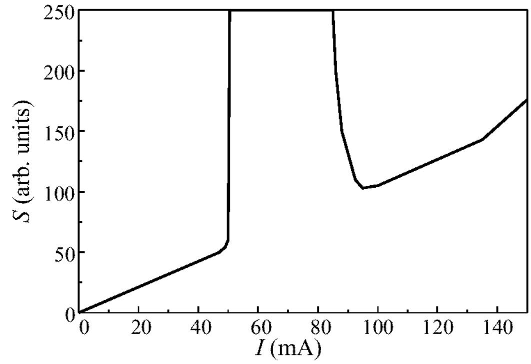

Fig. 1. Photodetector signal vs current.

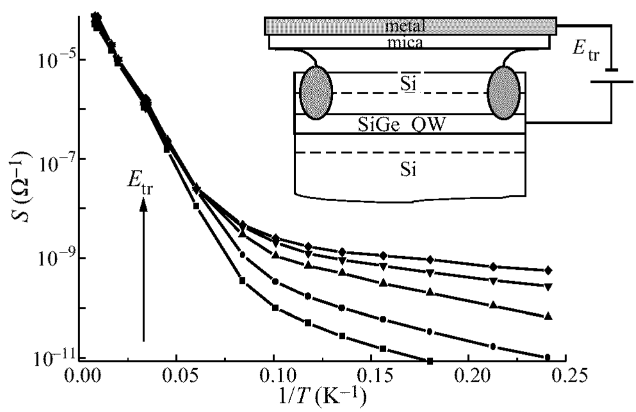

Fig. 2. Temperature dependence of lateral conductivity of SiGe QW at different voltages from 0 to 1.5 V.

An intense emission caused by Joule heating has usually been observed at the end of a 1.5 to 2 kV voltage pulse. However, in QW structures with well parallel polished opposite lateral (narrow) planes to form an optical resonator due to total internal reflection, the intense emission arose at essentially smaller fields, at the leading edge of the voltage pulse, and could not be, therefore, of thermal origin. Figure 1 shows the radiation intensity in dependence on the current along the quantum well. The radiation and current was registered at voltages above 300 V, it is the threshold of an impact ionization of acceptors in the QW. It is seen that there is a jump in radiation intensity which can be by orders of magnitude greater than spontaneous emission intensity. The intense emission exists in some range of currents and out of that the radiation-current curve is of the same character; this confirms non-thermal origin of the emission.

The intense radiation was coming out mainly from the narrow QW planes, that is natural for the resonator used. It was demonstrated by means of cutting filters that the wavelength of the emission is in the range from 50 to 100 μm. Of course, to make sure finally that the intense emission is stimulated, a spectrum of the emission should be measured.

To understand the cause of possible population inversion, we studied hole transport along the QW. Figure 2 shows the temperature dependence of a conductivity, σ, along the SiGe layer. One can see two activation-law regions in the curves. It has been shown by

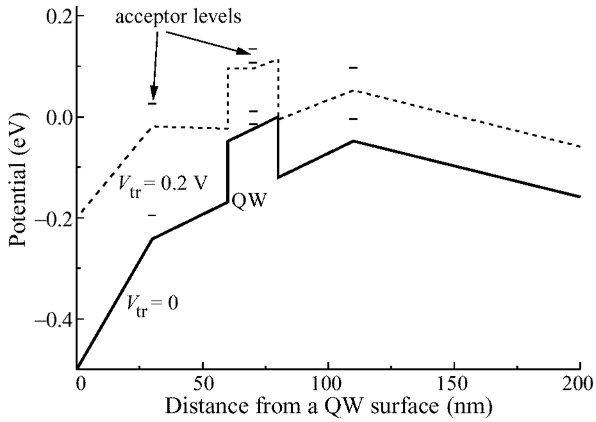

Fig. 3. Potential distribution across the QW for zero and 0.2 V transverse voltage applied between the QW and the surface.

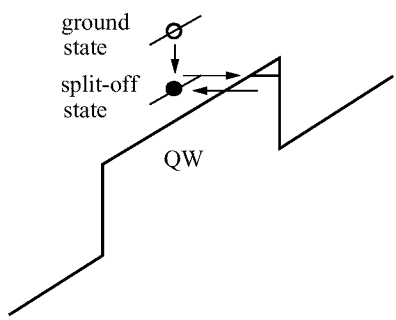

Fig. 4. Scheme of inversion.

means of Hall-effect and magnetoconductivity measurements [2] that the low-temperature part of the curves is due to the thermally activated hopping over neutral B centers. At higher temperatures, the conductivity is shown to be due to thermal activation of holes from the ground to strain-split B states following by hole tunneling into the QW valence band. The tunneling is possible due to inclining valence band profile by a transverse potential caused by hole capture at surface states which makes the surface charged.

This model is confirmed by transverse field-effect measurements. Besides of voltage applied along the QW, the voltage across the QW was applied. Different curves in Fig. 2 correspond to various transverse voltages. The lowest one is for zero transverse voltage. The external potential applied across the QW essentially increases the lateral low-T conductivity and decreases the activation energy, i.e. holes are transferred by transverse electric field from Si cup-layer surface into QW populating B levels.

The calculations of a valence band profile across the QW structure, free carrier concentration in the QW and acceptor population at various transverse voltages were performed by solving Poisson and Schrödinger equations with taking into account pinning the Fermi energy on the Si cup-layer surface. The energy gap, Δ, between the valence band top and the Fermi level fixed at the surface was regarded as a fitting parameter. The results are shown in Fig. 3. The best fit to the experiment was at $\Delta = 0.5$ eV.

The data presented permit us to propose the mechanism of a population inversion of strain-split acceptor levels. The scheme of the inversion is shown in Fig. 4. The transverse

potential caused by a surface charge inclines the valence band profile so that the split-off state of an acceptor becomes resonant. The electric field applied along the QW depopulates the ground state of an acceptor due to impact ionization while the split-off state can be filled to some degree because of tunnel exchange with the valence band continuum. Thus, this model is similar to that in uniaxially stressed bulk p-Ge [1].

2. Conclusion

The intense terahertz emission of boron doped strained SiGe QWs was observed. The stimulated character of the emission is confirmed by an existence of the threshold electric field and by the necessity of a resonator. The data obtained show that the strained quantum-sized semiconductor structures doped with acceptors are promised for lasing at THz frequencies.

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